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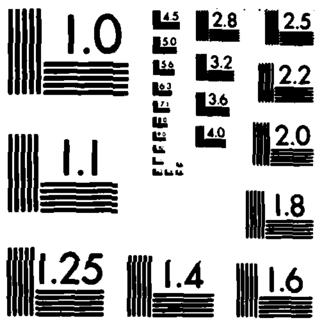

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Monterey, California

THESIS

SENSITIVITY ANALYSIS OF A COUPLED
ATMOSPHERIC-OCEANIC BOUNDARY LAYER MODEL

by

Rex Vernon Hervey

June 1984

Thesis Advisor: R.W. Garwood, Jr.

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Sensitivity Analysis of a Coupled Atmospheric-Oceanic Boundary Layer Model

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Submitted in partial fullfillment of the
requirements for the degree of

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ABSTRACT

In this thesis, ~~A~~ coupled, atmospheric-oceanic boundary layer model which provides a single station assessment and prediction capability has been developed from independently formulated one-dimesional oceanic and atmospheric bulk boundary layer models. Sensitivity analyses ~~are~~ were conducted to determine major differences in the response of the coupled model compared to those of the separate oceanic and atmospheric models. The general behavior of the coupled model is not significantly different from that of the atmospheric model alone over short term simulations (12 to 24 hours). However, under a certain set of limited conditions where winds are light and the lifting condensation level is close to the height of the inversion, large differences may occur. Major differences between the predicted evolution of the ocean boundary layer by the ocean model and coupled model are more common, and the short term predictive ability of the ocean model in coupled form is enhanced.

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I. INTRODUCTION

The ability to forecast the evolution of both the oceanic and atmospheric boundary layers is one of the primary concerns of the Navy's environmental tacticians. This is a result of the increased awareness by the fleet's operational commanders of the importance of environmental factors in influencing the effectiveness of their weapons and sensor systems and their growing demand for reliable environmental prediction schemes. It has become clear that an accurate knowledge of current and expected environmental conditions is likely to be one of the determining factors in the outcome of any at-sea tactical engagement.

The performance of nearly all electromagnetic (EM), electo-optical (EO), and acoustic systems is affected by conditions in either the atmospheric or oceanic boundary layers. In the atmosphere the formation of ducts and the trapping of EM radiation is controlled by the vertical gradient of the index of refraction which is a function of the vertical gradients of temperature, humidity, and pressure. The performance of EO systems is affected by small scale inhomogeneities in the index of refraction (due to turbulence), the water vapor content, and the amount of aerosols in the layers. In the ocean the most critical factor to the performance of sonar systems is the sound

velocity profile which is primarily a function of the near surface temperature structure. Time dependence is also critical since tactically significant changes in both layers may occur over time periods of 6 to 18 hours.

Since the performance of the aforementioned systems depends on the detailed structure of either the atmospheric or oceanic boundary layers, regional climatologies are not sufficient for operational predictions and models of the large-scale synoptic flows alone cannot simulate the required boundary layer processes. Furthermore, the structure and evolution of both boundary layers are influenced by their proximity to the air-sea interface and the interactions which occur at this boundary. It is therefore desirable to provide fleet units with a means of forecasting changes in the boundary layer conditions which may occur over short but tactically significant time periods and which fully account for the complex air-sea interactions that may occur.

One dimensional atmospheric (Davidson et al., 1984) and oceanic (Garwood, 1977) boundary models have been formulated which have demonstrated success in predicting the evolution of their respective layers. The next step is to successfully couple these proven models to better simulate the influence of the interactions at the air-sea interface.

This study is part of ongoing efforts in model development and evaluation to provide a shipboard based

computer model capable of reliably forecasting changes of boundary layer properties. Specifically, this study will attempt to determine if a preliminary coupled model (O'Laughlin, 1983) demonstrates significant differences in the simulation of boundary layer evolution from the separate, uncoupled models and if so, under what conditions these differences are most likely to occur.

II. BACKGROUND

A data set consisting of simultaneous oceanic and atmospheric soundings (Davidson et al.,1984) demonstrates that short time-scale air-sea interactions may occur which have a significant effect on the evolution of the oceanic (OBL) and atmospheric (ABL) boudary layers (Fig. 1). Significant responses are evident:

1) The ABL depth increases from 250 to 750 meters over the 48 hour period. The changes occur over relatively short intervals, from 20/0000 to 20/0400, and from 21/0000 to 21/0500 local time. The ABL depth remains nearly constant during the next 18 hour period.

2) The increase in the marine surface layer temperature is indicative of the entrainment of overlying warm air. This entrainment is presumably a factor in the wind speed increase over the same period. The speed increase, in turn, is believed to have contributed to the erosion by turbulent mixing of the transient warm shallow ocean thermocline. This mixed layer deepening event dropped the sea surface temperature by 1.5 degrees after 20/1800.

3) There is a rapid change in the ABL during the period from 21/0000 to 21/0500 which immediately followed the drop in sea surface temperature due to wind mixing.

Observations such as these have lead to the notion that a coupled atmospheric oceanic boundary layer model may be necessary to fully predict boundary layer evolution in view of the complex air-sea interactions which must be occurring. O'Laughlin (1982) attempted to simulate the evolution of the data set using the same prototype coupled model of the present study. His model results were unable to duplicate many of the details, particularly the changes in the OBL. He concluded that the inability to accurately reproduce the features of the data set was attributable to the horizontal movement of the research vessel through the complex ocean thermal structure of the California Current System during the period of data collection. He further found that simulations made with the uncoupled ABL model showed little difference from those made with the coupled ABL-OBL model. He concluded that under most conditions, prediction of ABL evolution by the coupled model is little improved over that of the uncoupled ABL model.

O'Laughlin's findings in his preliminary study have lead to the current sensitivity study, where it is intended to determine under what conditions the coupled model may predict evolution of the boundary layers which are significantly different from those made separately by the uncoupled models.

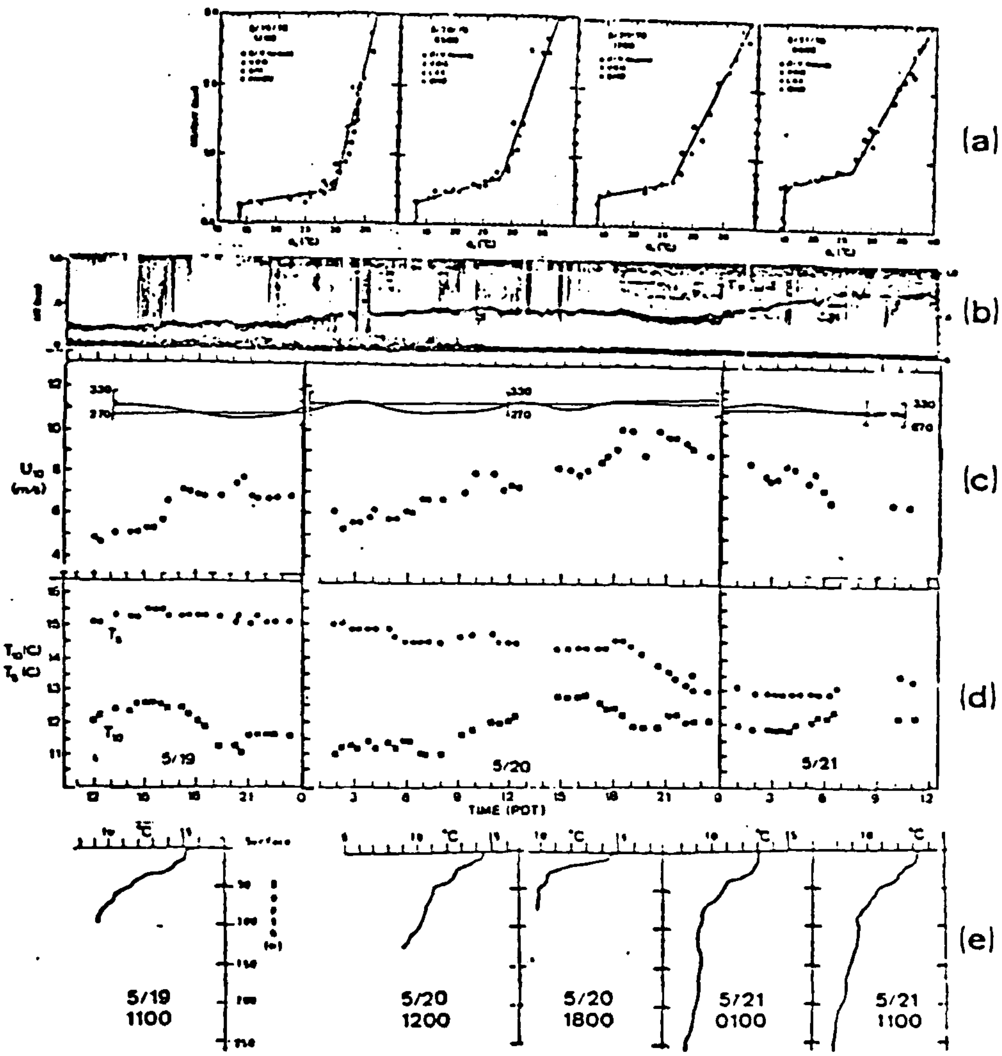

Figure 1. Atmospheric and Oceanic Mixed Layer Observations during CEWCOM-78. (a) potential temperature profiles (b) acoustic sounder record (c) 10 meter wind speed (d) 10 meter and surface temperature (e) XBT traces.

III. MODEL DESCRIPTION

A. THE AIR-SEA INTERFACE

The atmospheric and oceanic boundary layers are forced by the boundary conditions of the air-sea interface. These boundary conditions are the exchanges of heat, mass, momentum, and radiation which occur at or across this interface.

The atmospheric boundary layer (ABL) consists of a cool, moist, turbulent well-mixed layer (relative to upper air) in which the quantities of equivalent potential temperature and specific humidity are considered to be constant with height. The well-mixed layer extends from the sea surface to the capping inversion where pronounced changes (jumps) in the profiles of temperature and humidity occur. Above the inversion the air of the free (quasi-geostrophic) troposphere is warmer and dryer with potential temperature increasing and humidity decreasing with height. The turbulent fluxes of temperature and humidity at the surface and at the level of the inversion tend to change the value of the well-mixed quantities over time. Turbulence at the inversion also leads to the entrainment of free tropospheric air from above, and as a consequence, the upward growth of the layer. Large scale atmospheric forcing leads to subsidence. This vertical motion tends to limit or control

the vertical extent of the mixed layer. The time rate of change of the height of the inversion is therefore a result of a balance between the rate of entrainment and subsidence. The lifting condensation level (LCL), which is a function of temperature and humidity at the surface, determines the height at which moisture condenses within an air parcel that is lifted adiabatically. If the LCL is above the level of the inversion, the mixed layer will be cloud free. If, however, the LCL is found to be below the inversion, a layer of stratus is formed, extending from the height of the LCL to the top of the mixed layer.

The presence of stratus in the mixed layer has profound effects on the radiation budget, and hence, the evolution of both the ABL and OBL over time. Consequently, the sensitivity of the model to air-sea interactions which may be either a cause , or a result of stratus formation will be one of the focal points of this study.

Like the ABL, the oceanic boundary layer (OBL) is considered to be a turbulent, well-mixed layer which is separated from the dynamically stable free ocean below by the seasonal thermocline, where the gradients of momentum and density change abruptly. Both temperature and salinity are assumed to be homogeneous in the OBL. Density or buoyancy is dependent upon both temperature and salinity. However, in this study, temperature is considered to be the most important quantity, since the relative contribution of

salinity to density changes over short time scales is not significant (Miller, 1976). The well-mixed nature of the layer is maintained by turbulence created in response to the fluxes of momentum and buoyancy at the surface. If the combined effect of the surface fluxes is to cause cooling at the surface, free convective mixing will occur. The wind generated downward flux of momentum and the process of forced convective mixing may provide sufficient turbulent kinetic energy (TKE) to erode the thermocline and deepen the mixed layer through entrainment. Conversely, a shallower mixed layer will develop if the effect of the surface fluxes is to produce net warming at the surface and associated density stratification. A primary concern of this study is to determine if the atmospherically forced evolution of the OBL over short time scales can be shown to demonstrate a feedback effect on the ABL that otherwise might not have occurred. Profiles of the assumed structure of the OBL and ABL are depicted in Figure 2.

B. THE COUPLED MODEL

The two boundary layer models were first coupled by O'Laughlin (1982). The combined model consists of the ABL model described by Stage and Businger (1981) which was modified by Davidson et al (1983) and the OBL model of Garwood (1977).

The ABL model is a zero-order, two layer, integrated, well-mixed surface layer underlying a non-turbulent free atmosphere. As a zero order model, a discontinuity (jump) exists in the profiles ofthe well-mixed quantities since the inversion is assumed to have zero thickness. The ABL model predicts the time evolution of the well-mixed quantities of equivalent potential temperature (θe) and specific humidity (q). Lapse rates are assumed to remain constant at their initialization values. The time rate of change of the well-mixed quantities and their respective jumps at the inversion are given by the standard integrated forms (Tennekes and Driendocks, 1981):

$$h(Dx/Dt) = (w'x')_o - (w'x')_h + \text{source}$$

$$h(D\Delta x/Dt) = h\Gamma x(\partial h/\partial t) - (w'x')_o + (w'x')_h - \text{source}$$

Here Γ_x is the lapse rate of the quantity above the inversion and source is equal to $-(Fn_h - Fn_o)/\rho c_p$ for $x=\theta_e$ and equal to zero for x=q. Fn is the net radiativ flux. The subscripts 0 and h refer to surface and inversion height values respectively.

Bulk aerodynamic formulas are used to determine the surface fluxes of momentum, sensible heat and water vapor:

$$u* = Cd^{1/2}u$$

$$T* = Co^{1/2}(\Theta - \Theta)$$

$$q* = Co^{1/2}(q - q)$$

The fluxes are given by:

$$(u'w') = u*^{2}$$

$$(T'w') = u*T*$$

$$(q'w') = u*q*$$

where u* is the friction velocity, the subscript zero denotes the sea-surface quantity and Cd and Co are the stability-dependent drag and exchange coefficients.

The entrainment velocity parameterization of Stage and Businger (1981) is used to close the system of equations. This closure assumption is that the dissipation of turbulent kinetic energy is a fixed fraction of the production rate.

The long and short-wave radiation fluxes are computed separately. The long wave net radiation flux in the cloud case is calculated as a function of the cloud top temperature and the effective radiative sky temperature using the Stefan-Bolzmann law. In the cloud-free case, the net long wave flux is calculated from the water vapor and temperature profile. The net radiation fluxes are calculated at the height of the inversion and at the surface using the method (Fleagle and Businger, 1980) of integrating the flux emissivity profile. In the cloudy case effective sky temperature is obtained by integrating from the cloud top upward.

The short-wave radiation flux is calucuiated using the delta-Eddington method (Joseph et al. 1976). The incident flux at the top of the mixed layer is obtained from the flux at the top of the atmosphere and the average transmittance in each of 15 bands covering the spectrum from 0.2 um to [illegible] um. The application of this method is described by Fairall et al (1981).

The OBL model of Garwood (1977) is a one-dimensional, second order, bulk model. It uses the Navier-Stokes equation of motion with the geostrophic component eliminated, the continuity equation, the heat equation from the first law of thermodynamics, the conservation of salt equation, and an analytical equation of state. A buoyancy equation is generated from the heat and salt equations together with the equation of state, where conservation of buoyancy is employed as a generalization of the conservation of heat and salt mass. Separate vertical and horizontal equations for turbulent kinetic energy (TKE) are used with system closure obtained by mean turbulent field modeling of the vertically integrated equations for the individual TKE components, plus inclusion of the bulk buoyancy and momentum equations.

The fluxes of momentum, radiation, and latent and sensible heat at the sea surface determine whether the model will react in the retreat (shallowing) or entrainment (deepening) mode. If there is a positive buoyancy flux as a

result of cooling at the surface or sufficient wind-generated TKE for mixing, the layer will tend to deepen. If the surface fluxes lead to a net warming at the surface a shallower mixed layer will form provided wind stress is not large.

C. MODEL COUPLING

Coupling of the atmospheric and oceanic models is accomplished by matching their respective fluxes of momentum, sensible heat, latent heat, and radiation at the air-sea interface. The fluxes of momentum, latent heat, and sensible heat are calculated by the atmospheric model via bulk formulas as functions of wind velocity, humidity, and the air-sea temperature difference. These fluxes are calculated at each time step for use by the atmospheric model, but are also passed to the oceanic model for its use after unit conversion (MKS to CGS). The net long-wave radiation flux for use by the oceanic model is calculated by the atmospheric model as a function of sea surface temperature and the downward flux of long-wave radiation at the inversion. The incident short-wave radiation at the sea surface is calculated by the delta-Eddington method as discussed in the description of the atmospheric model.

The separately formulated atmospheric and oceanic models were originally devised to be numerically integrated using different time steps. The atmospheric model has a time step

of 30 minutes, whereas the oceanic model has a time step of 60 minutes. In the coupling scheme, the respective model's time steps were left unaltered. This was believed to be acceptable provided there is little change in sea surface temperature over any one hour period. The ocean model calculations are undertaken only at every other 30 minute time step. Figure 3 is a schematic diagram of the computational steps in the coupled ABL-OBL model.

D. MODEL INITIALIZATION

Initialization of the atmospheric model requires the directly-measurable quantities of air temperature, specific humidity and sea surface temperature, plus quantities which can be routinely obtained from an atmospheric sounding. Mixed layer winds, subsidence, and thermal and moisture advection must be prescribed for each time step during the model run, and must be obtained from means other than direct measurement, such as large scale synoptic forecasts. Accurate prediction of subsidence may be particularly difficult to obtain. Gleason (1982) examined several methods for predicting subsidence. He found that even the most accurate method suffered from a large standard deviation. The atmospheric model is very sensitive to subsidence variation.

The oceanic model requires temperature, salinity, and velocity profiles for initialization. In most cases only a

temperature profile is routinely available. Over short time scales this poses no problem since the salinity and velocity profiles may be set constant with depth with negligible effect on the model's predictive ability. A complete list of quantities required for model initialization is given in Table I.

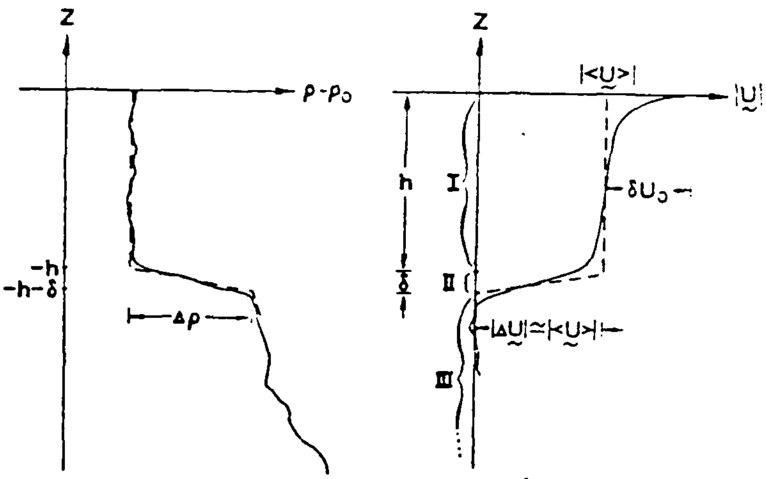

Figure 2a. Idealized density and mean velocity profiles of the ocean mixed layer. Region I is the fully turbulent mixed layer. Region II is the entrainment zone. Region III is the under... stable watermass.

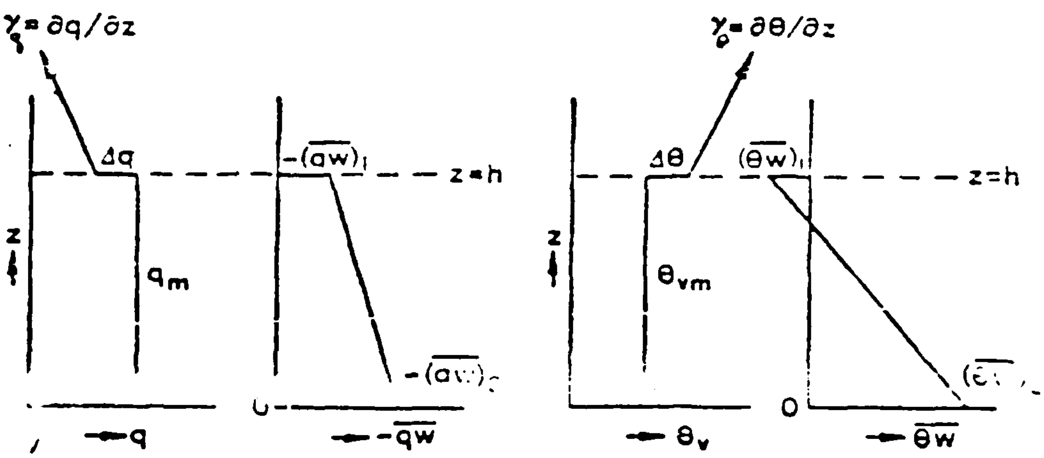

Figure 2b. Assumed profiles of temperature (Θ) and humidity (q) and their assumed profiles.

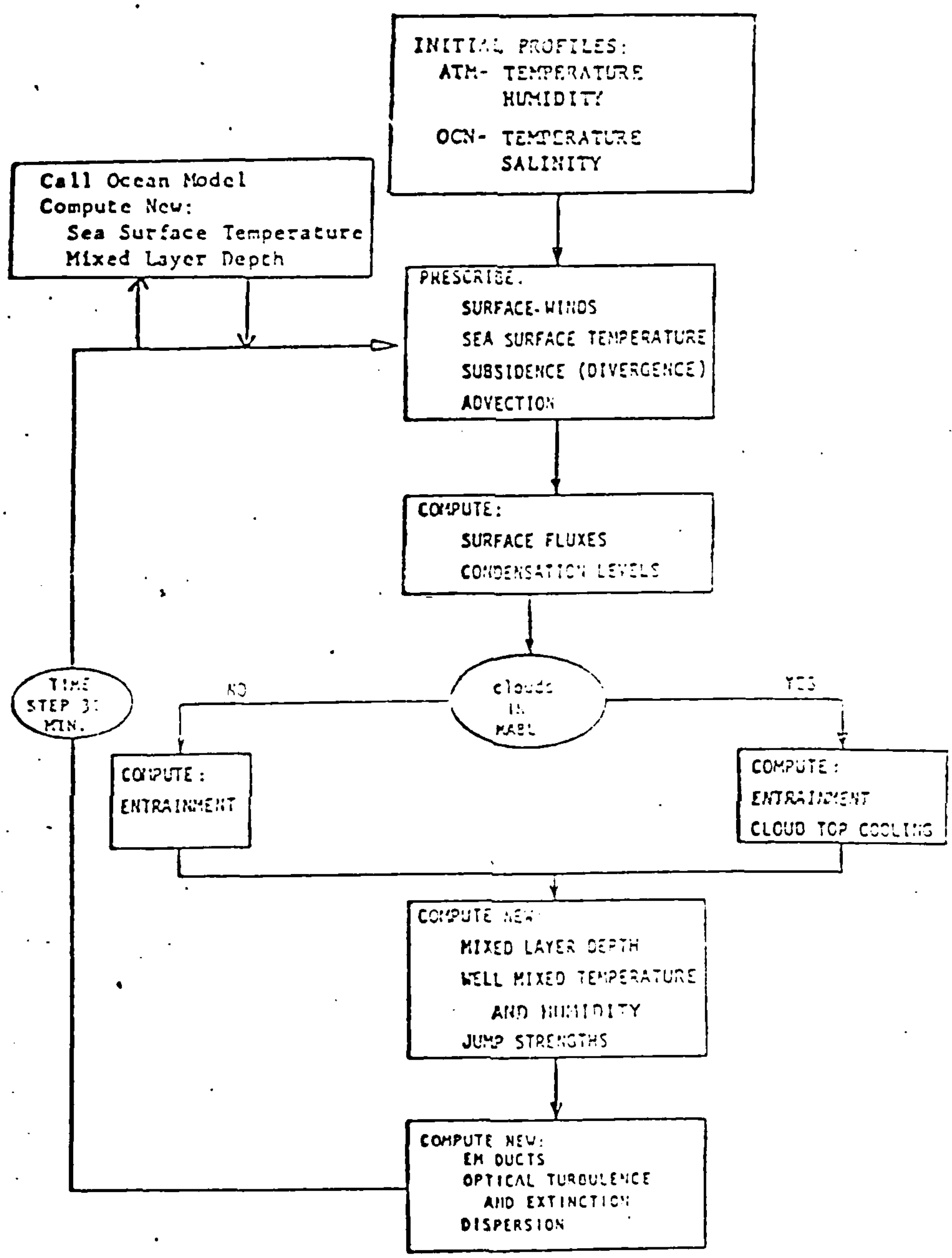

Figure 3. Schematic of Atmospheric and Oceanic Coupled Model. The ocean model is called at every other 30-minute time step.

TABLE I.

List of Quantities Required to Initialize the [illegible]

ABL MODEL:

Observed Quantities
- Time of Observation (Start)
- Julian Day (JDAY)
- Latitude (LAT)
- Initial Inversion Height (Zi)
- Sea Surface Temperature (SST)
- Mixed Layer Potential Temp (TH)
- Jump in Potential Temp at Inversion (DTH)
- Potential Temp Lapse Above Inversion (DTHDZ)
- Specific Humidity in the Mixed Layer (QP)
- Specific Humidity Jump at the Inversion (DQP)
- Specific Humidity Lapse Rate Above Inversion (DQDZ)

Prescribed Quantities
- Subsidence (Ws)
- Thermal Advection (DTDT)
- Moisture Advection (DQDT)
- Wind Speed (U10)

OBL MODEL:

Temperature Profile
- Mixed Layer Depth (H)
- Jump at the Base of the Mixed Layer (DTO)
- Gradient Below the Layer (DTODZ)

Salinity Profile

Velocity Profile

IV. METHODS

Sensitivity analyses to determine major differences in the response of the coupled ABL-OBL model versus those of the uncoupled models were conducted. In the coupled model, the only contribution the OBL model makes to the ABL model is sea surface temperature (SST), hence uncoupling of the ABL model is achieved simply through setting the SST constant. Uncoupling is achieved in the OBL model by maintaining the atmospheric values of temperature, humidity and long wave radiation constant, so the fluxes of temperature, moisture, and long wave radiation are determined only by changes of the ocean thermal structure in relation to a constant atmosphere. The momentum and short wave radiation fluxes are provided to the uncoupled OBL model in the same manner as in the coupled ABL-OBL model.

The analyses were conducted by performing a series of model simulations where in each case the coupled and separate ABL and OBL models were initialized, as far as applicable, with the same set of initial conditions. The prescribed variables of wind speed, subsidence, thermal advection, and moisture advection were systematically varied to determine conditions where the coupled model responded in a significantly different manner from the separate ABL or OBL models. Although simulations were conducted with a

variety of ocean profiles, including deep, moderate, and shallow mixed layers, for reasons which will be discussed in a subsequent section, only shallow mixed layers appear to have a significant impact on the coupled model's predicted evolution of the atmospheric layer. Consequently, most examples presented deal primarily with results obtained using only shallow mixed layers.

Model simulations were initialized from soundings obtained during the Cooperative Experiment on West Coast Oceanography and Meteorology (Fairall et al., 1977) from 21 September to 12 October 1976 (CEWCOM-76) and CEWCOM-78 (Fairall et al., 1978) from 5 to 23 May 1978. Both experiments were conducted off the coast of southern California in the vicinity of the Channel Islands. Lists of the initial conditions for each of the model simulations discussed in the results section are included in Tables II and III.

The most significant results of the analyses are presented in this study, where a sufficent number of model simulations will be discussed to allow the inference of the coupled model's behavior where air-sea interactions have a significant effect on the predicted evolution of the atmospheric and oceanic boundary layers.

TABLE II.

Initial Quantities for CASES 1 through 5

Values of initial quantities held constant for all CASES

START	JDAY	LAT	Zi(m)
1900	277	35.0	507.0m
LCL	TH(deg)	DTH(deg)	DTHDZ(deg/m)
677.0	19.8	3.5	.0052
SST(deg)	QP(g/kg)	DQP(g/kg	DQDZ(g/Kg/day)
21.1	10.2	-2.4	-0.0025

Value of prescribed quantities by CASE

CASE	U10 m/s	Ws m/s	DTDT deg/day	DQDT g/day	H m	DTQ deg	DTQDZ deg/m
1	3.0	-.003	1.5	-1.0	1.5	2.0	-0.15
2	3.0	-.003	0.0	0.0	1.5	2.0	-0.15
3	5.0	-.003	1.5	-1.0	1.5	2.0	-0.15
4	3.0	-.003	1.5	-1.0	11.5	0.0	-0.15
5	3.0	-.003	0.0	0.0	11.5	0.0	-0.15

TABLE III.

Initial Quantities for CASE 1

Values of initial quantities

START	JDAY	LAT	Zi(m)
0500	140	35.0	351.0m
LCL	TH(deg)	DTH(deg)	DTHDZ(deg/m)
316	12.0	12.7	0.0047
SST(deg)	QP(g/kg)	DQP(g/kg)	DQDZ(g/kg/day)
14.0	7.35	-4.5	-0.0005

Value of prescribed quantities

case	U10	Ws	DTDT	DQDT	H	DTO	DTODZ
	m/s	m/s	deg/day	g/day	m	deg	deg/m
1	2.5	-.003	0.0	0.0	30.0	0.0	-0.10

V. RESULTS

A. STRATUS FORMATION

A primary goal of this study is to determine the conditions under which the coupled model will predict stratus formation differently from that of the uncoupled ABL model. The results of coupled model and uncoupled ABL model simulations which demonstrate this are presented. Model simulations are initialized with an atmospheric sounding taken at 1900 local from the CEWCOM-76 data set. In this case the wind speed is set to a nearly constant 3.0 m/s, the thermal advection to 1.5 deg./day, the moisture advection to -1.0 g/kg/day, and the subsidence to -0.003 m/s. The remainder of atmospheric variables are left as observed during the CEWCOM-76 experiment. The ocean mixed layer is initially shallow at 1.5 m with a temperature jump of -2.0 deg at the base of the mixed layer. The below layer gradient is -0.15 deg/m. The initial values of the variables for these simulations are summarized under CASE 1 of Table II.

For the CASE 1 ABL model simulation (Fig. 4) the moderate value of subsidence and the low rate of entrainment due to light winds have the combined effect of decreasing the height of the inversion over the 24 hour period of simulation from 607 m to 438 m. As a result of positive

thermal advection the air temperature rises at a near steady rate up to 12 hours after the start of the simulation where an increased rate of heating occurs as solar insolation becomes a factor. After 22 hours of simulation (1700 L) solar insolation is no longer effective and thermal advection is balanced by a reduced sensible heat flux at the sea surface, causing the air temperature to become constant at 20.7 deg. Through evaporation at the sea surface and a relatively low rate of entrainment the specific humidity increases throughout the course of the simulation from 10.2 g/kg to 12.2 g/kg. The net effect of the increasing air temperature combined with countering effect of increasing humidity is to reduce the height of the LCL from 577 m to a height approximately 20 m above the height of the inversion and to maintain the slight difference through the course of the simulation.

The results of the CASE 1 uncoupled model simulation, where stratus formation does not occur, may be compared to the CASE 1 coupled model simulation (Fig. 5). In this case the model is initialized in the same manner except variations in the sea surface temperature are allowed to influence the ABL model as changes in the ocean thermal structure evolve. Through evaporative and sensible cooling at the sea surface the shallow mixed layer erodes rapidly allowing the SST to quickly cool after the start of the simulation (-2.0 degrees in 12 hours). The cooler SST

results in reduced sea-air temperature and humidity fluxes and the air temperature increases only slightly during the first 12 hours of simulation. The increasing specific humidity is not balanced by increasing air temperature and the LCL falls below the height of the inversion forming a layer of stratus at 11 hours after initialization. After stratus formation the atmospheric layer is evolved quite differently by the coupled model. As a result of radiative cooling at the top of the stratus layer the temperature of the atmospheric layer rapidly decreases. Entrainment due to radiative cooling increases the height of the inversion to 824 m and introduces dryer air into the surface layer, resulting in a steady decrease of the specific humidity.

In the CASE 1 model simulations, critical values of thermal and moisture advection are selected which, in the case of the uncoupled ABL model, maintain the height of the LCL slightly above that of the inversion, and in the case of the coupled model, allows the LCL to fall below the inversion and form stratus. The critical nature of the selected thermal and moisture values in the CASE 1 simulations may be appreciated by a comparison with the CASE 2 simulations. Here the prescribed value of thermal and moisture advection are set to 0.0 deg/day and 0.0 g/kg/day respectively, with all other variables remaining the same as CASE 1.

In the CASE 2 ABL model simulation (Fig. 6) the absence of positive thermal advection results in the air temperature cooling slightly. As a consequence, the LCL falls below the inversion and stratus formation occurs after 4.5 hours of simulation. The evolution of the atmospheric layer predicted by the CASE 2 coupled model simulation (Fig. 7) is quite similar. Again, the air temperature decreases slightly (although at a greater rate than in the ABL model case) and stratus forms after 4 hours. The effect of a rapidly cooling sea surface temperature is to cause the formation of stratus one time step earlier in the coupled model case. Additionally, because the air temperature is lower throughout the simulation (differing by -0.5 deg after [illegible] hours), the final height of the LCL is predicted to be [illegible] m lower by the coupled model. Differences between all other atmospheric variables are negligible.

In the CASE 2 results the effect of the rapidly cooling SST is not as apparent as in the CASE 1 results where the coupled model demonstrates significant differences from the uncoupled ABL model. Clearly, the relationship between the LCL and the height of the inversion is critical to whether or not the coupled model behaves much differently from the uncoupled ABL model.

B. WIND SPEED EFFECTS

The effect of increased wind speed on the model results is demonstrated by the CASE 3 simulations. In this case the

prescribed winds are increased to a near constant 5.0 m s while all other variables remain the same as in CASE 1. In both the coupled model (Fig. 8) and the uncoupled ABL model (Fig. 9) simulations the effect of the higher wind speed is to generate greater turbulence in atmospheric layer which in turn causes a greater rate of entrainment at the inversion. This results in the height of the inversion descending at a decreased rate compared to the CASE 1 simulations. As the LCL falls below the inversion height, after 4 hours for the uncoupled ABL model, and after 5 hours for the coupled model, stratus formation occurs. This differs considerably from the CASE 1 results, where for the ABL model stratus formation did not occur, and for the coupled model where stratus formed after 11 hours. The difference between the coupled model and uncoupled ABL model CASE 3 simulations are much less drastic. Even though the increased wind speed produces a more rapid erosion of the mixed layer and cools the SST to a lower temperature than in CASE 1, the differences between atmospheric layer quantities predicted by the coupled model and the uncoupled ABL model are slight. The only major exception is air temperature which has a final value 0.8 deg cooler in the coupled model simulation. Clearly, the influence of coupling the separate models is more important in the light wind case where there is less tendency for the system to be dominated by the effects of

large scale atmospheric forcing and where the more subtle influence of SST changes may have the opportunity to act.

C. OCEAN THERMAL STRUCTURE

The effect of a deeper ocean mixed layer on the response of the coupled model may be observed by examining the CASE 4 results. In this case the model is initialized with an ocean mixed layer depth of 11.5 m and a gradient below the mixed layer of -0.15 deg/m. All other initial variables are the same as in CASE 1. For the coupled model simulation (Fig. 10) the mixed layer erodes from an initial depth of 11.5 m to 13.9 m and the SST cools from 21.1 deg to 20.8 deg after 15 hours of simulation. Because the LCL remains above the height of the inversion stratus does not form and solar insolation is effective in warming the sea surface and forming a shallow mixed layer. By mid-afternoon the SST has warmed to its initial value of 21.1 deg. The effect of the deeper mixed layer is to prevent the SST from dropping sufficiently to reduce the warming rate of the atmosphere enough to cause the LCL to fall below the inversion. The overall result is little different from that obtained from the CASE 1 uncoupled ABL model results where the SST is kept constant. On the other hand, they are quite different from the CASE 1 coupled model results where the rapid erosion of the shallow mixed layer and consequent cooling of the SST promoted the formation of stratus.

Clearly, the nature of the ocean thermal structure has a profound effect on the evolution of the atmospheric layer predicted by the coupled model. The most important effects are found where the ocean mixed layer is very shallow and where there is a relatively large jump or steep gradient at the base of the mixed layer, as in CASE 1. The effects become increasingly less important with more moderate mixed layer depths and negligible for deep mixed layer depths (greater than 30.0 m).

D. EFFECT OF COUPLING ON THE OBL MODEL

The advantage of predicting the evolution of the ocean boundary layer with the coupled model is demonstrated by the results of the CASE 5 simulations. This case is initialized with light winds and the same CEWCOM-76 sounding as CASES 1 through 4. The temperature and thermal advection are set to zero and the ocean model is initialized with a 11.5 m mixed layer depth and a below layer gradient of -0.15 deg/m. In the case of the uncoupled OBL model (Fig. 11) the atmospheric variables are set constant maintaining clear-sky conditions throughout the course of the simulation. As cooling at the sea surface proceeds through the hours of darkness the mixed layer erodes to a depth of 14.1 m. After 16 hours (1100 L) warming by solar radiation is sufficient to cause the formation of a shallow (2.8m) mixed layer which persists through the afternoon until eroding to a depth of

6.8 m by the end of simulation. The SST drops from 21 deg. to a minimum of 20.3 deg. and rises to 20.9 deg. by the end of the simulation. In contrast, the coupled model (Figure 12) predicts the formation of stratus 4 hours after initialization. As a result of the formation of stratus, the coupled model predicts a 77% reduction in the amount of solar radiation available at the ocean surface. The stratus layer also acts to cool the air temperature through radiational cooling (-1.3 deg) and reduce the specific humidity through an increased rate of entrainment at the top of the atmospheric layer. The combined result of the reduced solar radiation and increased sensible and latent heat fluxes is to maintain net cooling at the sea surface. The mixed layer erodes throughout the course of the simulation without the formation of a shallow mixed layer.

The most important feature of the coupled model's application in simulating ocean boundary evolution is its ability to predict the formation of stratus. The dramatic effect stratus formation has on the radiation budgets of both the atmospheric and oceanic boundary layers and on changes to air temperature and humidity can not be simulated by the uncoupled ocean model alone.

E. RESULTS OF A 72 HOUR SIMULATION

To observe the response of the coupled and uncoupled HBL models over longer time periods an atmospheric sounding from

the CEWCOM-78 data set is used to initialize the models for a 72 hour simulation. The set of observed and prescribed initial conditions (CASE 5) is contained in Table III. In this case the atmospheric layer is initially cloud covered with light winds (2.5 m/s). The initial air and sea surface temperatures are much cooler than in previous examples, at 12.0 and 14.0 m respectively and the inversion and LCL heights are lower. The ocean mixed layer is relatively deep at 30.0m with a below layer gradient of -10.0 deg. In the original CEWCOM-78 sounding the air temperature was observed to be only slightly lower than the SST. For this simulation the air temperature is lowered to 2.0 deg. below that of the sea surface temperature with the purpose to observe any difference between equilibrium states achieved by the coupled and uncoupled ABL models.

1. <u>Day 1</u>

As a result of the imposed light winds entrainment is ineffective at mixing warm upper-air into the surface layer and the effect of radiational cooling immediately lowers the air temperature. As the air temperature rapidly falls the LCL lowers and the stratus layer grows thicker. During the first 4 hours of simulation the air temperature drops 1.5 deg and the LCL has fallen from 316 m to 173 m. By 4 hours after the start, solar radiation is effective in reducing the rate at which the air temperature falls. Consequently, the height of the LCL is maintained. Since the rate of

entrainment nearly balances subsidence the height of the inversion is nearly constant and drops only slightly during the first 24 hours of simulation. As a result of the relatively light winds the evaporation rate is insufficient to counter the introduction of dry upper-air into the atmosphere's surface layer and the specific humidity decreases rather steadily throughout the first 24 hours. At 12 hours after initialization (1700 L) solar radiation is no longer effective in heating the atmosphere and the air temperature cools rapidly. In response, the LCL falls and by the conclusion of the first day is lowered to 46 m.

The initial response of the coupled model (Fig. 14a) is the same as the uncoupled ABL model, except that with the formation of a shallow mixed layer a considerable warming of the sea surface results. The warming of the sea surface, from 14.0 to 15.2 deg, reduces the rate of cooling of the air temperature and as a result the LCL remains higher, dropping only to 63.0 m.

2. Day 2

By the second day of simulation both models have reached a near equilibrium state. In the case of the coupled model (Fig. 14a) the mixed layer erodes only to a depth of 6.1 m thus maintaining a warmer SST than in the case of the uncoupled ABL model. The effect of the warmer SST is to maintain a higher average air temperature than that exhibited by the uncoupled ABL model (Fig. 13b). In

both cases the LCL rises during the daylight hours as heating occurs as a result of solar radiation. However, because of the average higher air temperature of the coupled model the LCL falls only to a height of 44.0 m compared to 23.0 m for the uncoupled ABL model.

3. Day 3

During the Day 3 simulation (Figs. 13c and 14c) the pattern of Day 2 is nearly repeated. The average air temperature in both models continues to decrease slightly, although the decrease occurs at a higher rate for the uncoupled model. In fact, by the completion of the third day's simulation, a major event has occurred. In the uncoupled ABL model the LCL has essentially reached the surface, predicting the occurrence of fog. In the case of the coupled model, the LCL remained well above the surface at 38.0 m.

While this case demonstrates some significant differences between the coupled and uncoupled models, it must be noted that the simulations were conducted with relatively light wind speeds. With only a slightly higher wind speed (4.0 m) and all other conditions the same, differences between the two models become negligible. The higher wind speed prevents the formation of a persistant shallow ocean mixed layer by the coupled model. Thus, the SST is not appreciably warmed in an average sense, and no additional heating is provided to the atmosphere.

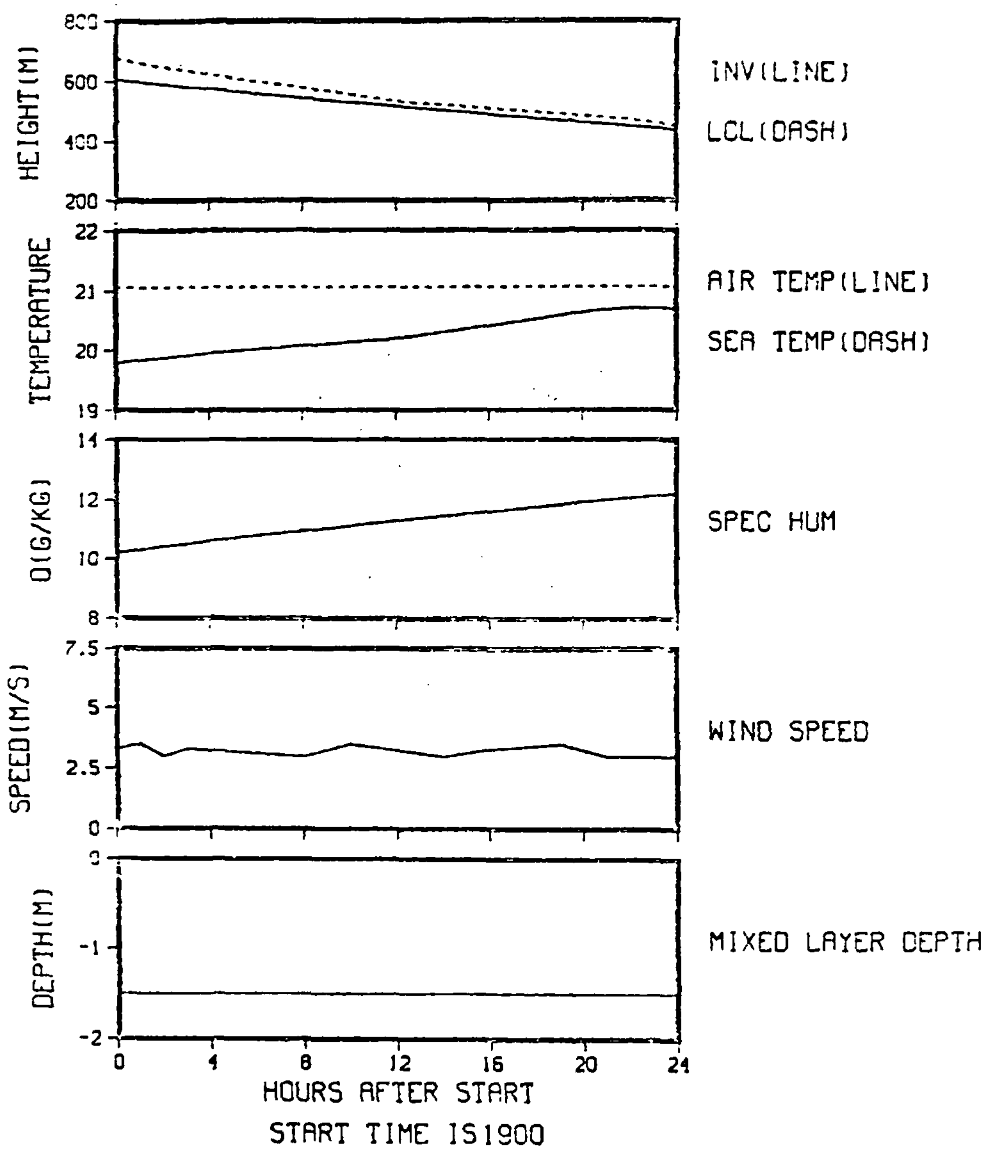

Figure 4. CASE 1 24 Hour ABL Model Simulation.

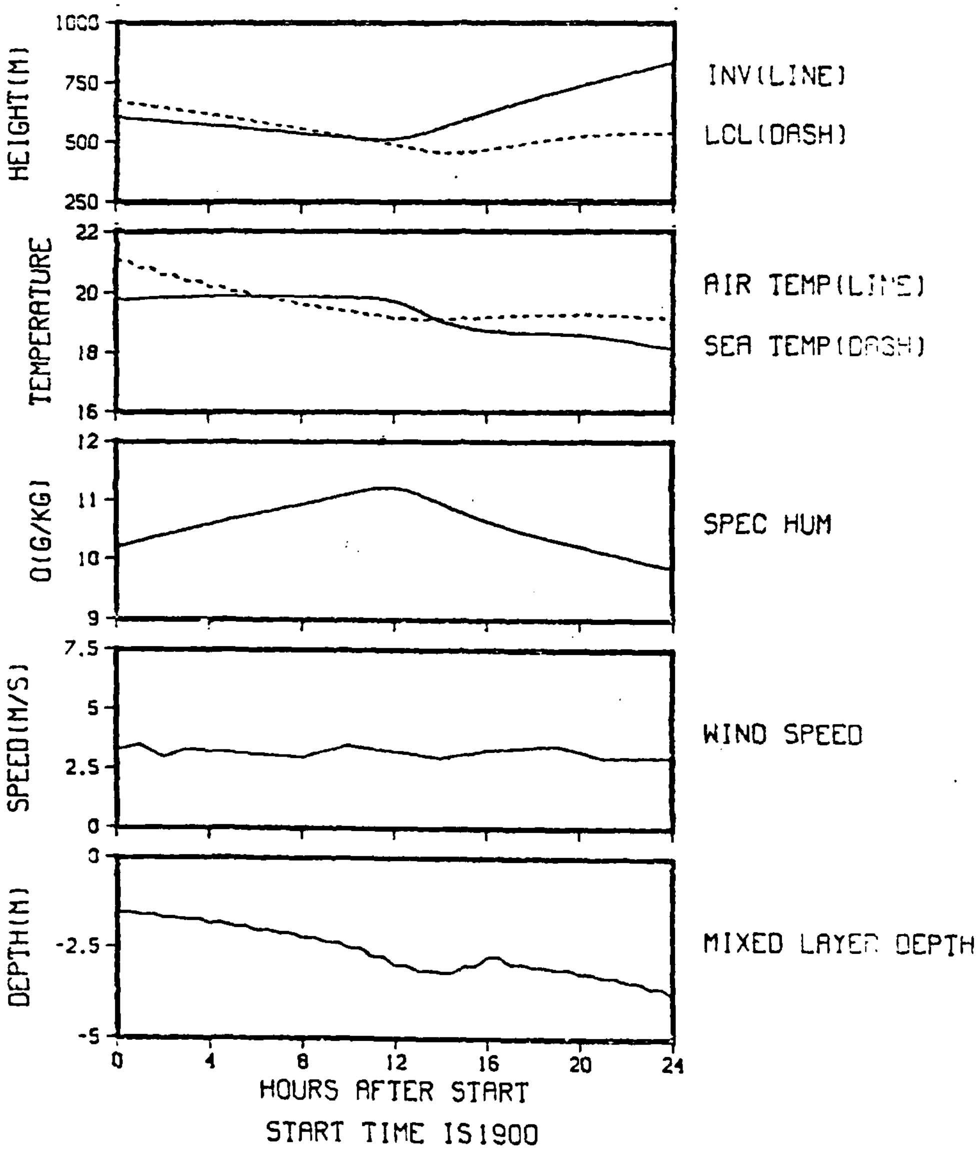

Figure 5. CASE 1 24 Hour Coupled Model Simulation.

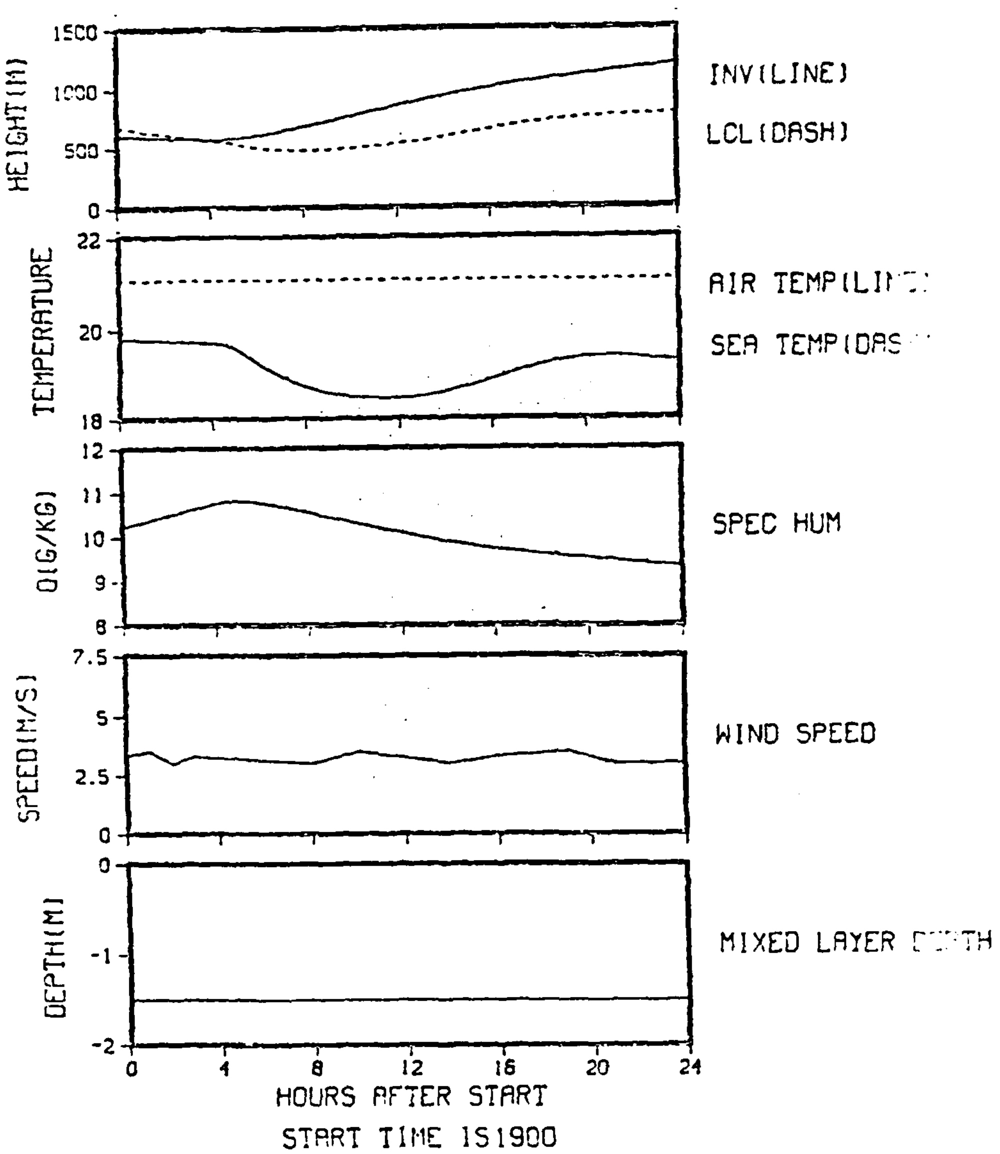

Figure 6. CASE 2 24 Hour ABL Model Simulation.

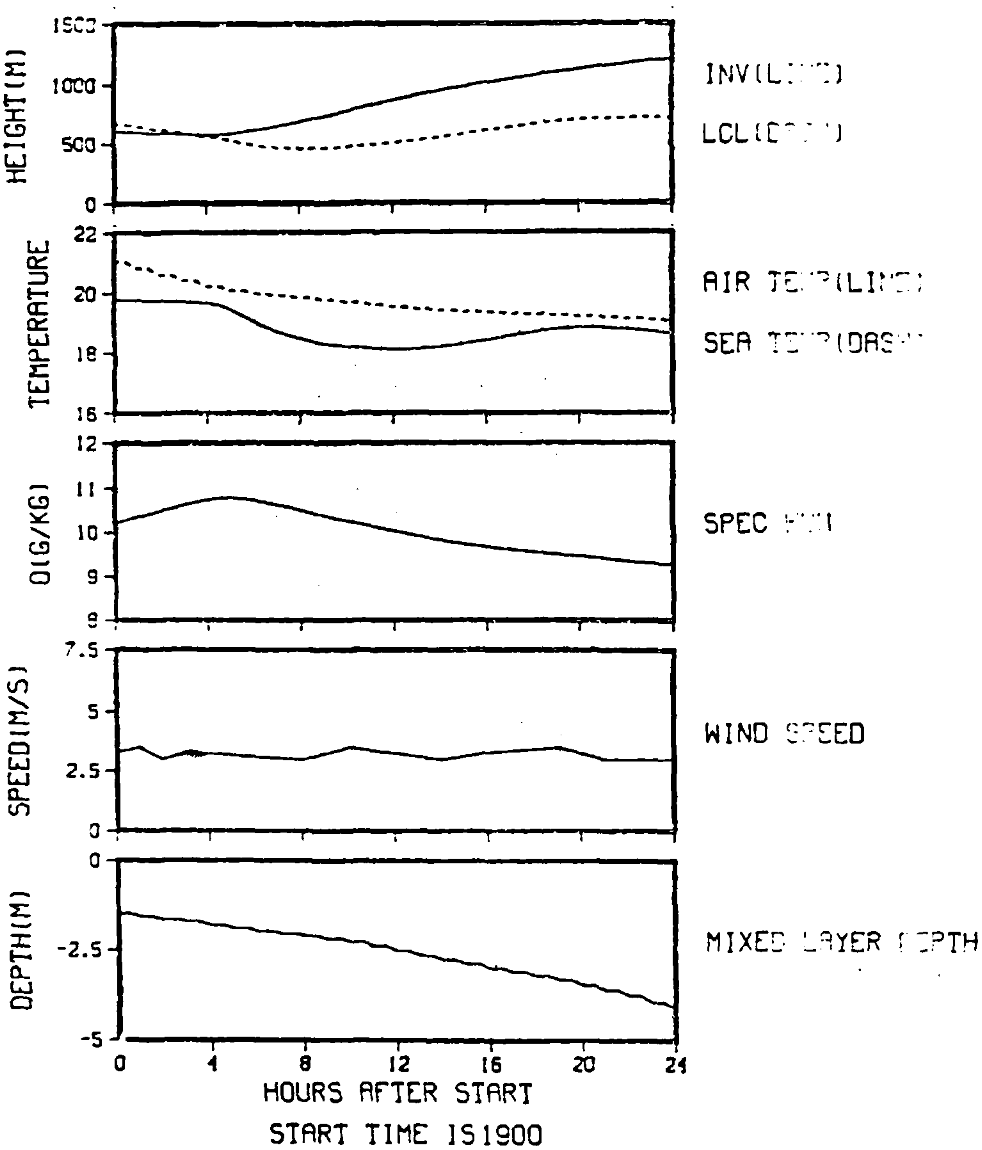

Figure 7. CASE 2 24 Hour Coupled Model Simulation.

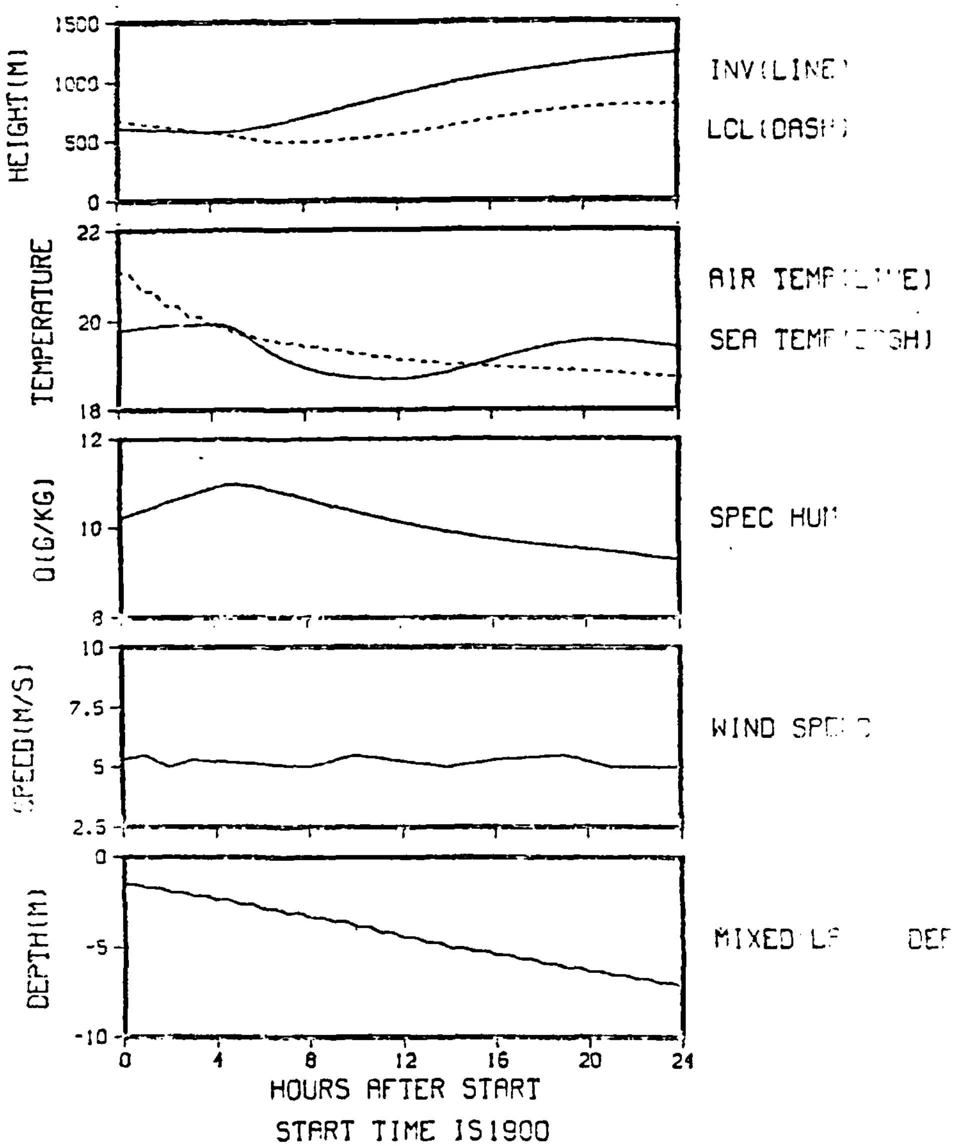

Figure 8. CASE 3 24 Hour Coupled Model Simulation.

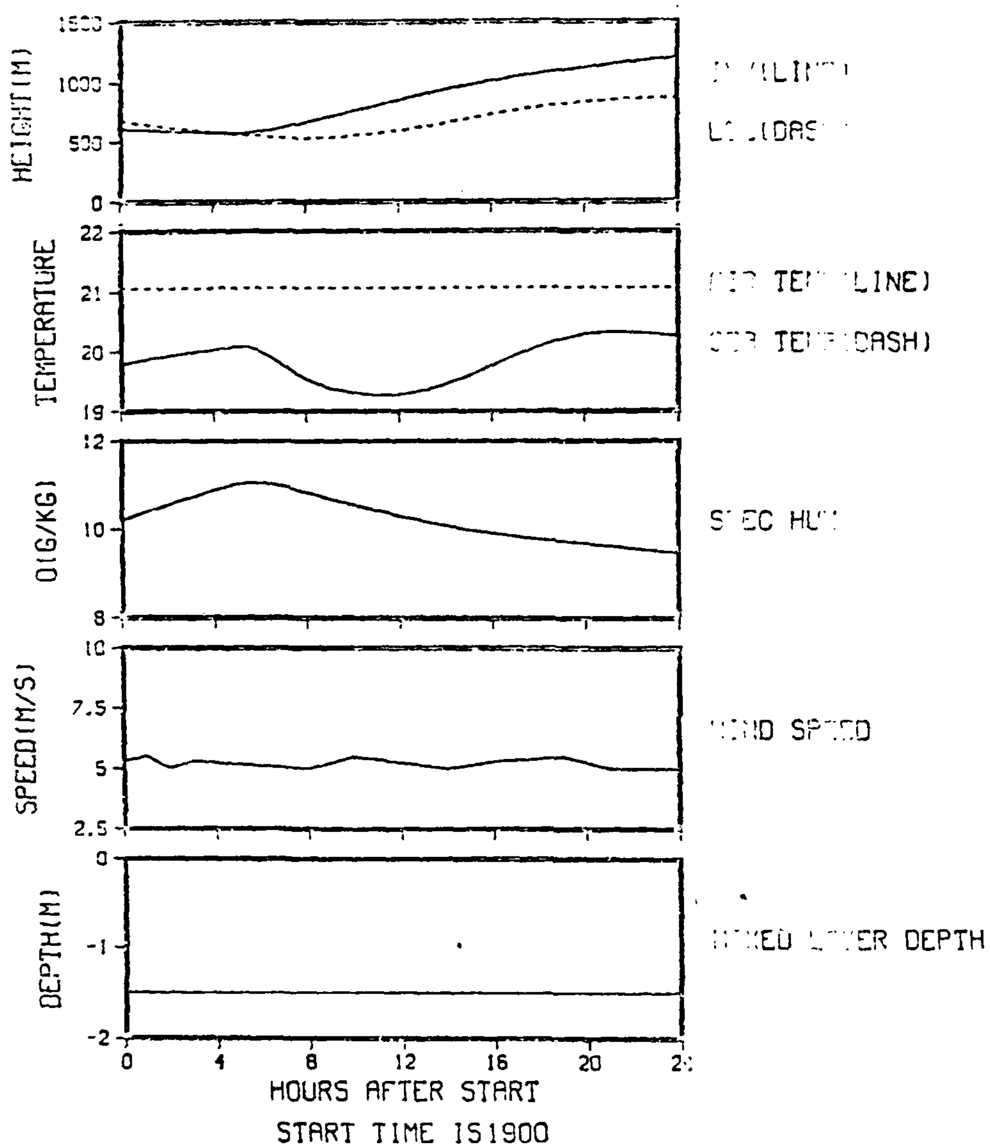

Figure 9. CASE 3 24 Hour ABL Model Simulation.

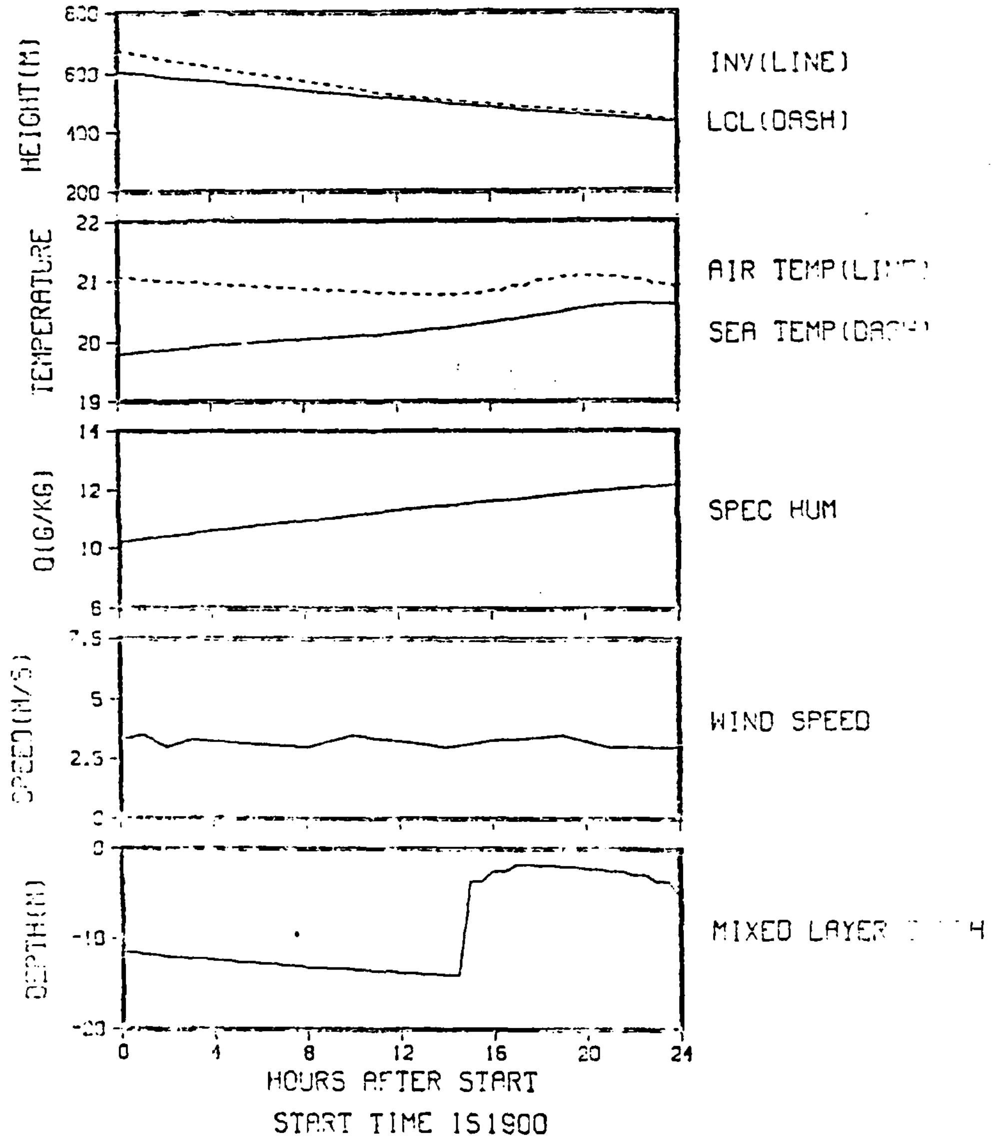

Figure 10. CASE 4 24 Hour Coupled Model Simulation.

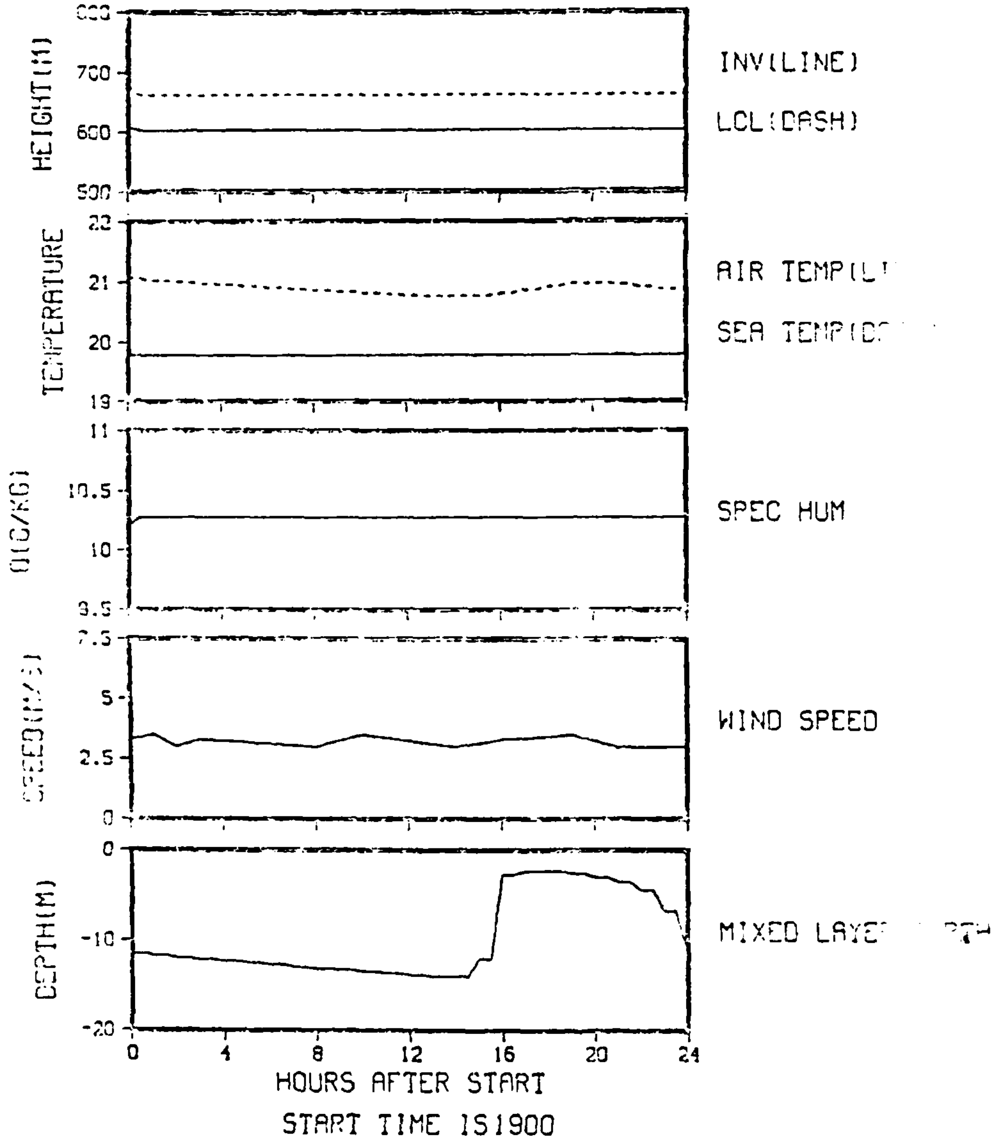

Figure 11. CASE 5 24 Hour OBL Model Simulation.

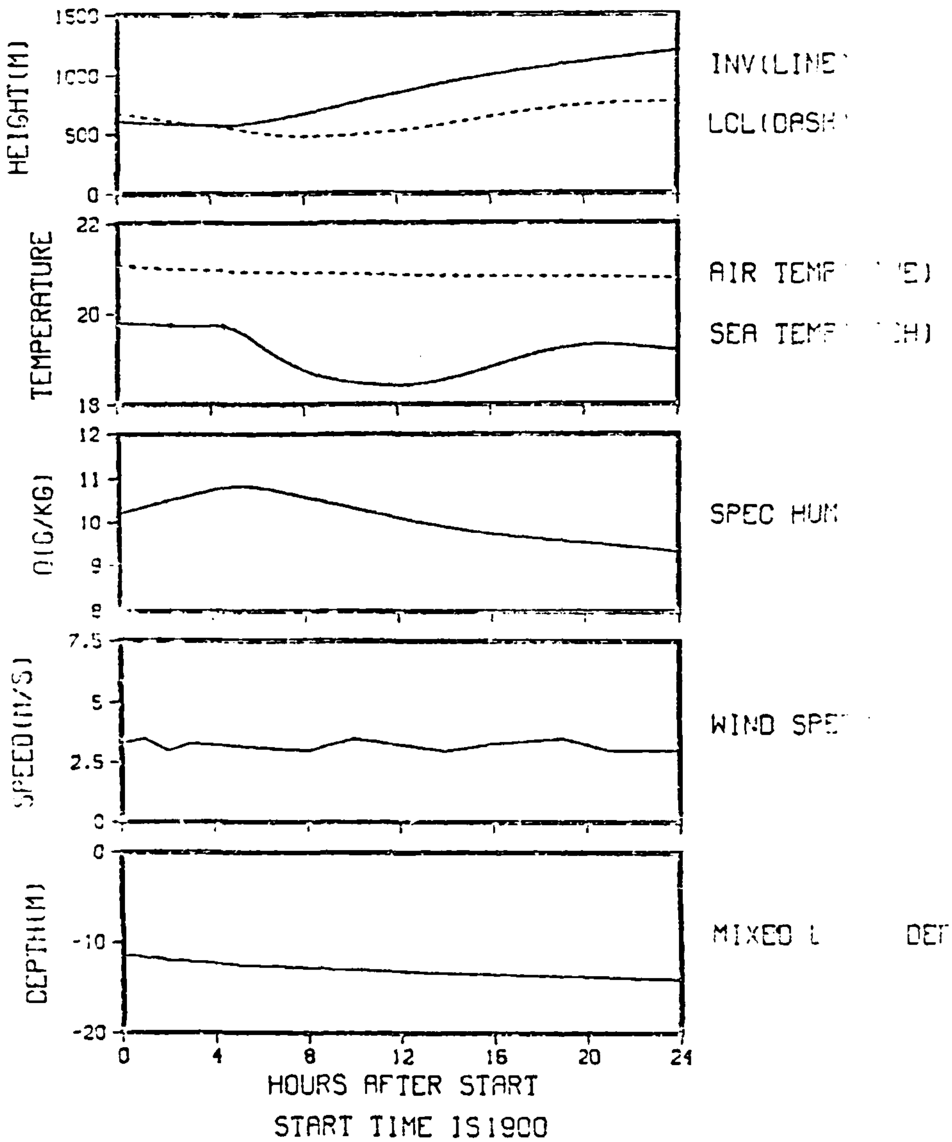

Figure 12. CASE 5 24 Hour Coupled Model Simulation.

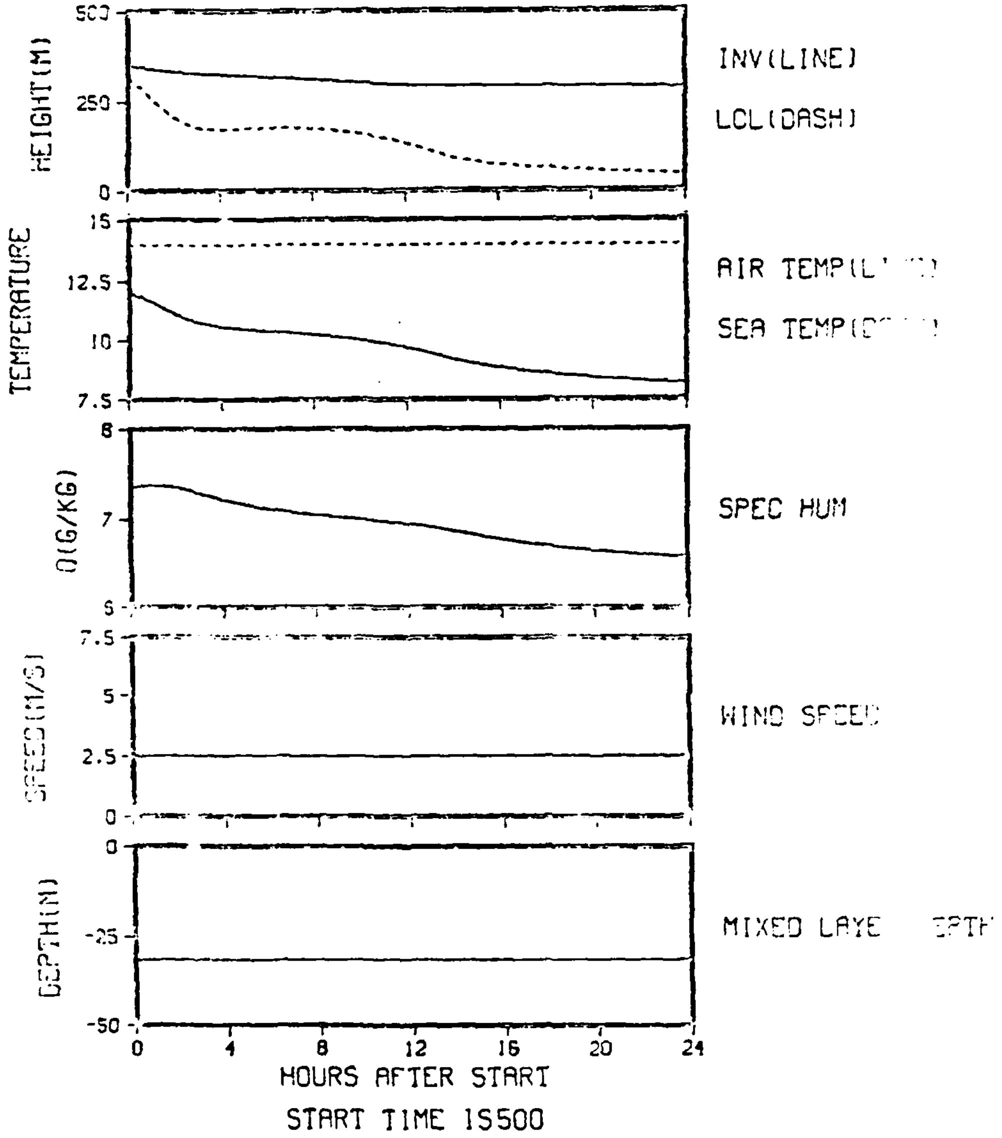

Figure 13a. CASE 6 72 Hour ABL Model Simulation, Day 1.

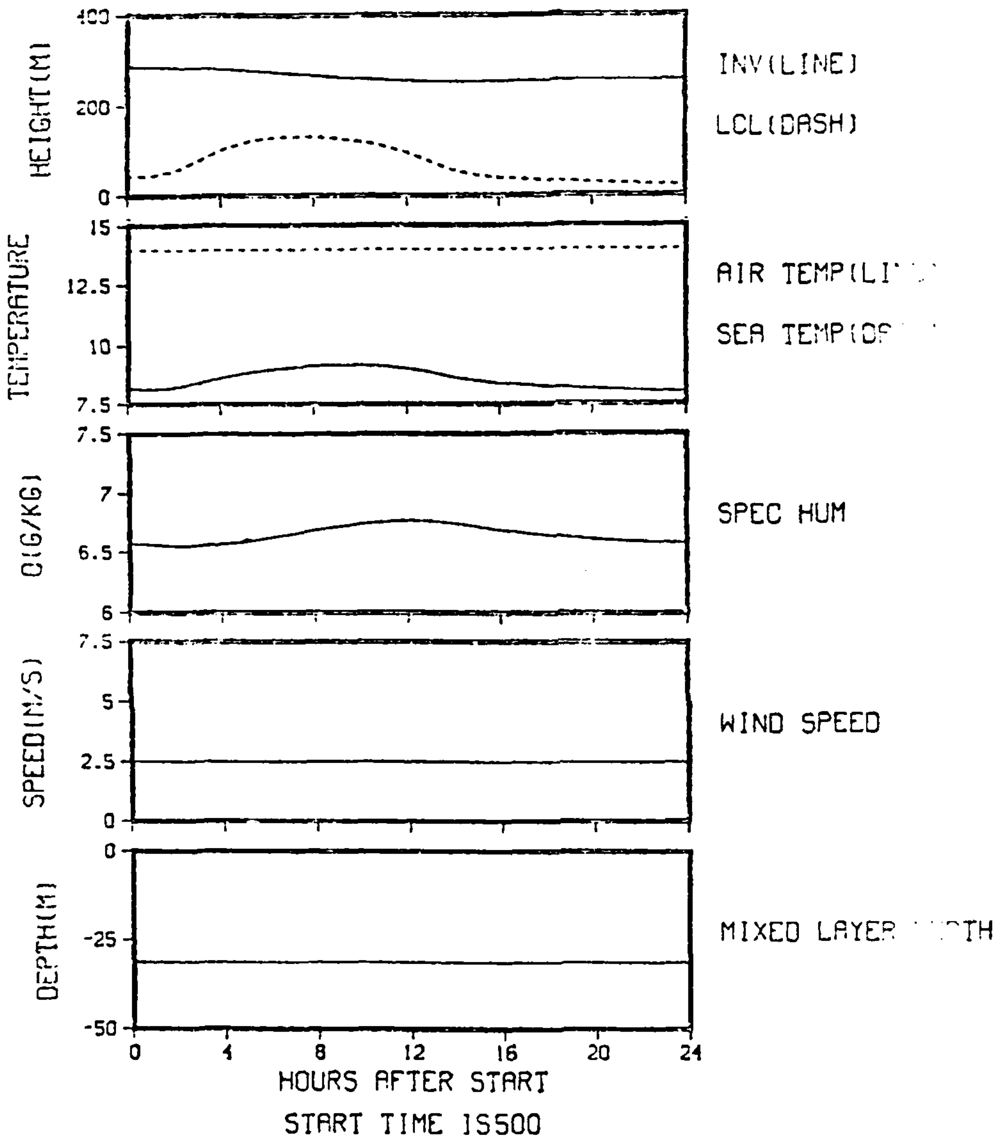

Figure 13b. CASE 6 72 Hour ABL Model Simulation, Day 2.

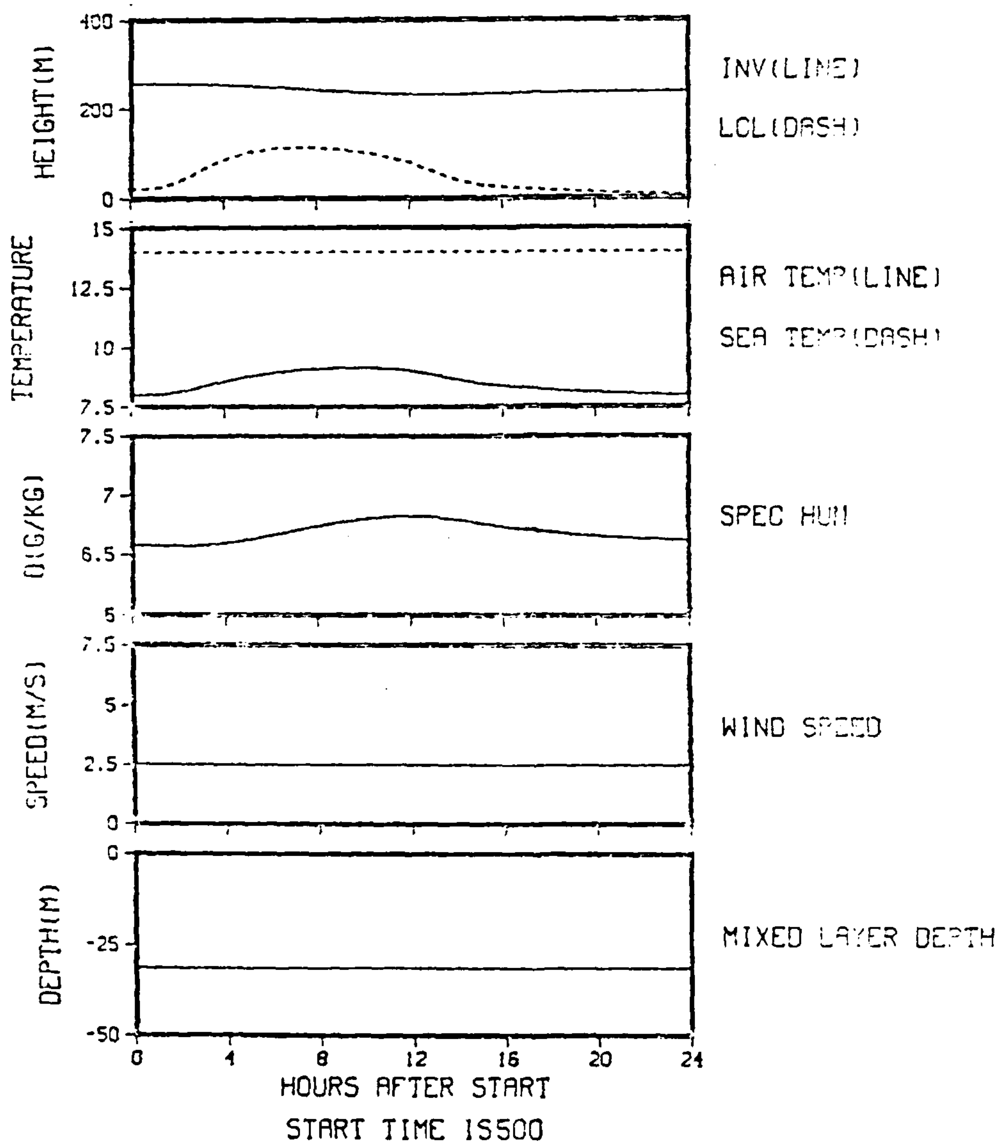

Figure 13c. CASE 6 72 Hour ABL Model Simulation, Day 3.

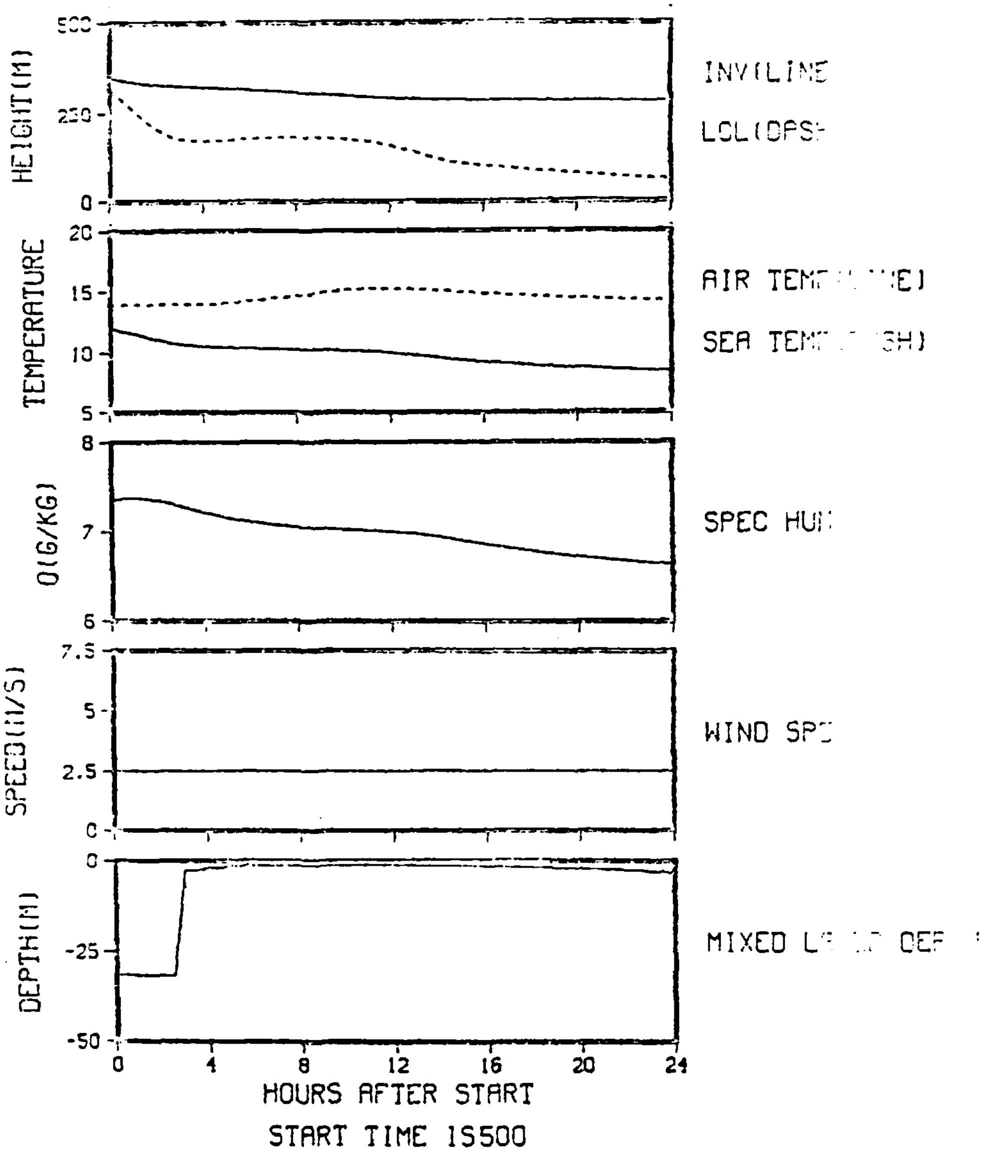

Figure 14a. CASE 6 72 Hour Coupled Model Simulation, Day 1.

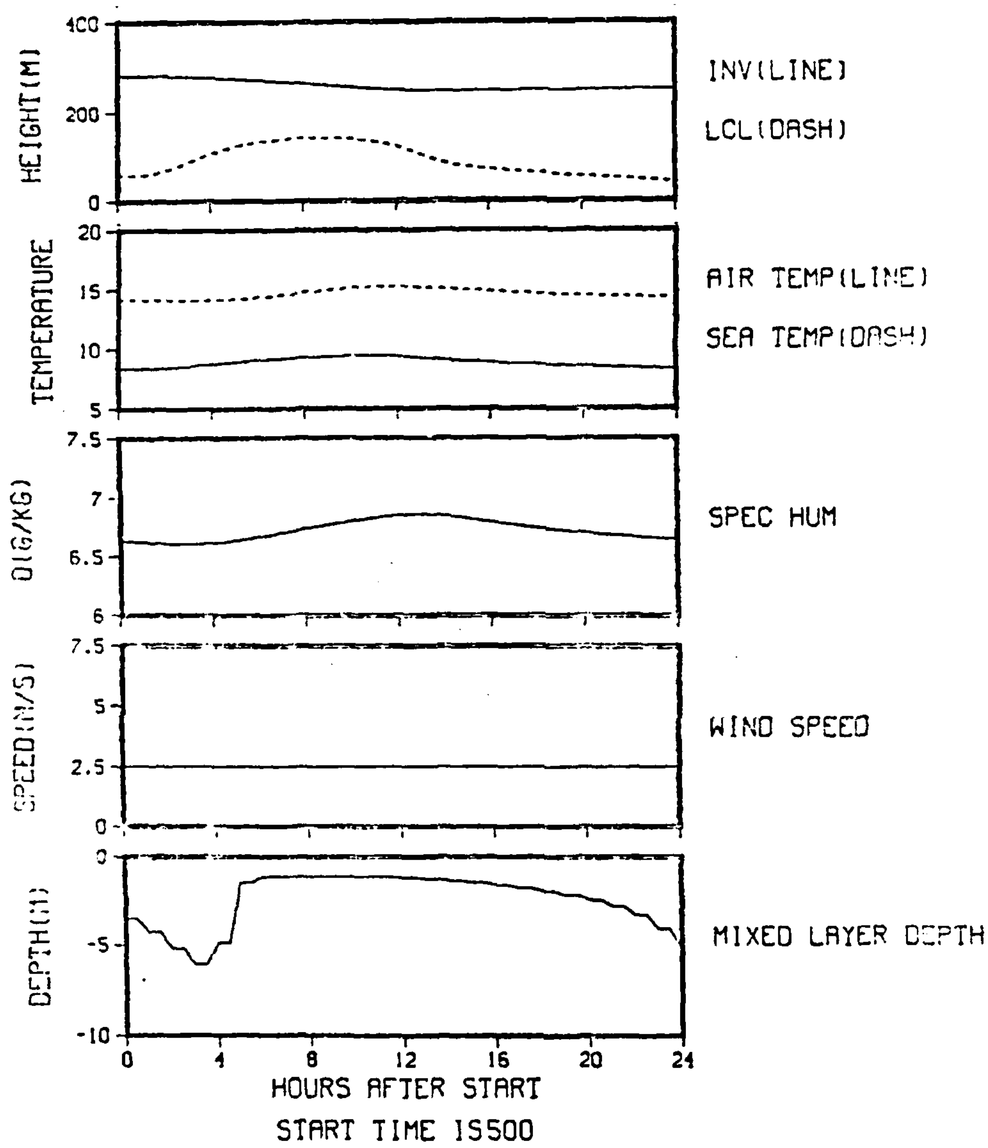

Figure 14b. CASE 6 72 Hour Coupled Model Simulation, Day 2.

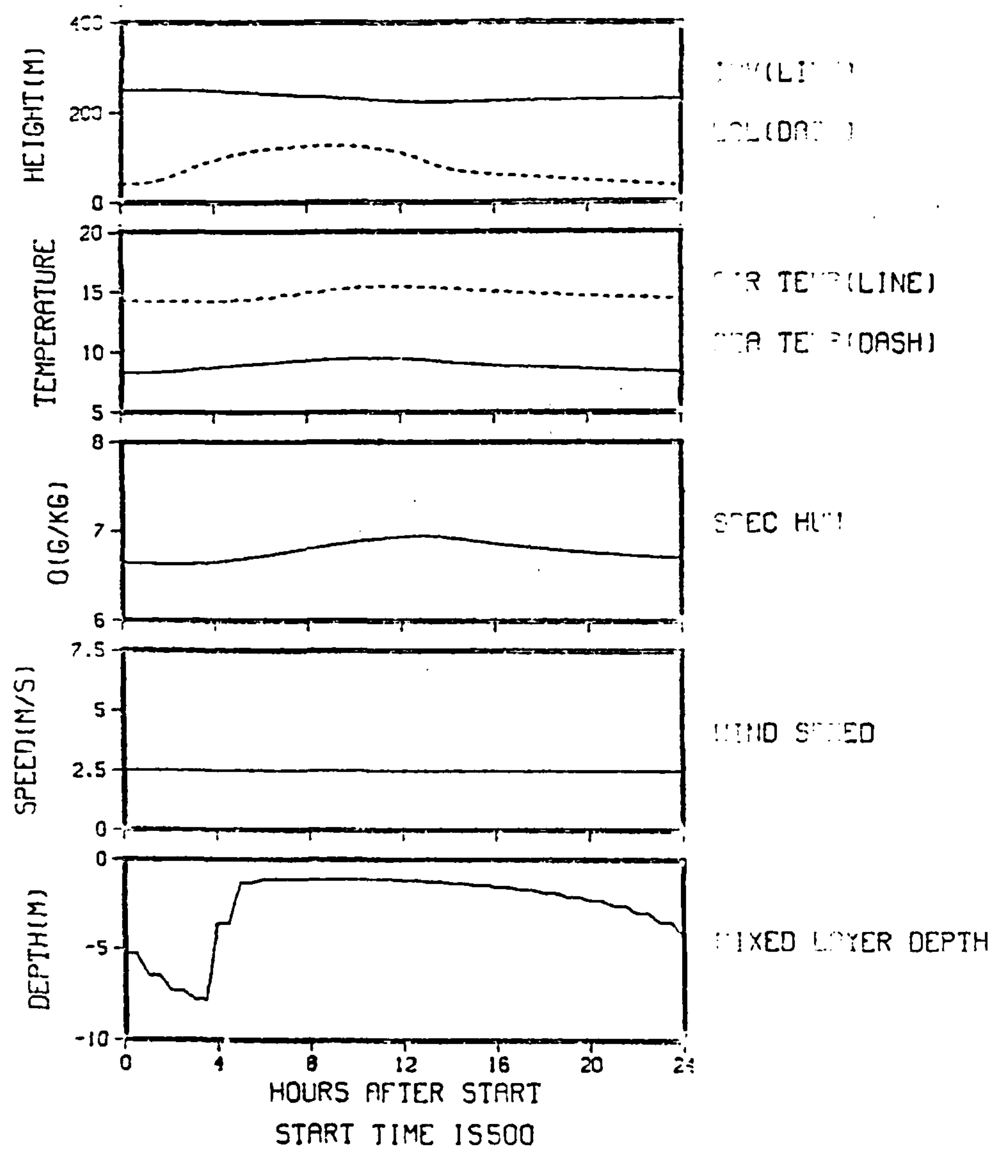

Figure 14c. CASE 6 72 Hour Coupled Model Simulation, Day 3.

VI. CONCLUSIONS

Although the examples discussed in this study were selected to emphasize major differences in the response of the coupled model compared to that of the uncoupled ABL model, under most commonly occurring conditions differences are minor, and there is little advantage in the predictive ability of the coupled model over that of the uncoupled ABL model. The considerable effort required to define those initial conditions under which major differences occur seems to bear this out. In addition, uncertainties in the predicted values of wind speed, subsidence, thermal advection, and moisture advection may have a greater influence on the predictive ability of the coupled model than any advantages gained through coupling. However, a great deal of effort has been expended in the development of the ABL model in portraying as accurately as possible the many physical factors involved in the evolution of the atmospheric layer. The inclusion of the capability to provide ocean forcing in the model is worthwhile on this basis alone.

Conditions under which major differences may be observed between the coupled and uncoupled ABL model are summarized as follows:

1. Major differences are more likely under light wind conditions (less than 5.0 m/s). Forcing of the atmospheric layer by stronger winds tends to overwhelm the more subtle influence of changes in SST.

2. The formation of stratus may be predicted better by the coupled model in those cases where the LCL maintains a height slightly above the inversion. Under such conditions fluctuations in SST can be critical.

3. Differences may be more significant where the ocean mixed layer is shallow with a steep gradient below the layer. Rapid decreases in SST may occur under these conditions which can have a strong influence on the evolution of the atmospheric layer.

4. Short term changes in SST can have a significant effect on the formation of fog when a low altitude stratus layer already exists. In modeling such cases, the coupled model can demonstrate significant differences from the ABL model.

Although under most conditions the benefits of coupling to the ABL model may be minor, this is not the case for the OBL model. The predictive ability of the OBL model may be enhanced significantly through coupling, where a more physically accurate portrayal of the atmospheric forces driving the OBL may be acheived. Realistic modeling of radiation and latent and sensible heat fluxes over short time scales can be provided to the OBL model in no other

way. As demonstrated, this is particularly true where stratus formation is predicted by the ABL model.

In the absence of shore support or for a rapid short term prediction, the coupled model offers a multi-purpose single station assessment and prediction capability. The coupled model also has the potential to become a valuable tool for the study of processes involved in air-sea interactions. As an example, the model could be used in the study of air-sea processes impacting air mass transformations, as in the case of cold air outbreaks over warm tropical waters. Further studies of the model's capabilities should include verification against an actual data set where the effects of advection and vessel movement are at a minimum. The data set should include those conditions, as pointed out, which provide the greatest likelihood of showing major differences in the response of the coupled model versus that of the uncoupled OBL and ABL models.

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